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Cognition in Scientific and Everyday Domains: Comparison and Learning Implications

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Abstract

An analysis and comparison of everyday life and the domain of science reveals significant differences in their goals and in the cognitive means used to attain these goals. Students' lack of awareness of these differences can lead to pervasive learning difficulties in their study of science. Thus many students (a) have erroneous conceptions of scientific goals, (b) import goals and ways of thinking which are effective in everyday life but inadequate in science, and (c) devise ways of thinking ill suited to science. Additional complications arise because science taught in schools often differs both from actual science and from everyday life. Students' learning difficulties are thus increased because scientific goals are distorted and scientific ways of thinking are inadequately taught. The preceding analysis suggests some empirical investigations and instructional improvements.

Introduction

Many students have substantial difficulties in learning science at the high school or college levels. Some of these difficulties are due to students' naive preexisting notions about the physical world. For example, students often believe that motion cannot occur without the presence of a force, or that an object moves in the direction of the force acting on it. Many such preexisting ideas are well documented (e.g., Caramazza, McCloskey, & Green, 1981; Clement, 1982; Cohen, Eylon, & Ganiel, 1983; diSessa, 1982, 1983; Driver, Guesne, & Tiberghien, 1985; Gunstone, 1987; Halloun & Hestenes, 1985a, 1985b; Helm & Novak, 1983; McCloskey, Caramazza, & Green, 1980; McDermott, 1984; Trowbridge & McDermott, 1980, 1981; Viennot, 1979; White, 1983). Other difficulties are due to the need in science to deal with abstract concepts and to solve complex problems (Chi, Feltovich, & Glaser, 1981; Chi, Glaser, & Rees, 1981; Heller & Reif, 1984; Labudde, Reif, & Quinn, 1988; Larkin, 1981; Larkin, McDermott, Simon, & Simon, 1980; Reif, 1983, 1987a, 1987b).

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This article identifies a potentially more pervasive source of students' difficulties, rooted in the fact that science is deliberately devised to attain special goals. Thus it is "artificial," in the sense used by Simon (1981), and is in several respects distinctly different from the "natural" knowledge of everyday life. The differences lead to significant learning difficulties because many students do not adequately understand the goals of science nor the kinds of cognitive processes needed to deal with this unfamiliar domain. Hence students often pursue inappropriate goals and resort to inappropriate cognitive means.

Persons familiar with a particular knowledge domain have ordinarily learned to function well in that domain; they understand its goals and use cognitive means well adapted to attain these goals. For example, most people cope successfully with the cognitive demands of everyday life. Similarly, experienced scientists cope successfully with the cognitive demands of the scientific-knowledge domain.

However, difficulties can be expected whenever someone tries to deal with a previously unfamiliar knowledge domain. In particular, our interest will be focused on pervasive learning difficulties experienced by students trying to learn about the unfamiliar knowledge domain of science.

The previously cited references provide impressive evidence that it is difficult to change students' naive conceptions, preconceptions, and misconceptions about the physical world. Even greater difficulties can be expected in attempts to change students' conceptions about the goals of science and about useful cognitive processes in this domain. Indeed, the required change involves then not only particular concepts or misconceptions, but general ideas about scientific goals and ways of thinking.

The aim of this article is to compare in detail scientific and everyday knowledge domains so as to reveal the distinctive differences between their goals and the cognitive processes used to attain them. This comparison will lead us to discuss the following educationally important issues:

- Because of deficient knowledge about the goals and requirements of science, students often pursue inappropriate learning goals including (a) transferring everyday goals into science where these goals are not appropriate, and (b) having misconceptions about scientific goals.
- Because of deficient knowledge about the kinds of cognition useful in science, students often use cognitive means ill-adapted to the scientific domain, including (a) transferring methods, effective in everyday life, into the scientific domain where they are inadequate, and (b) devising methods ill suited to scientific work.
- The situation is even more complex because "school science" (i.e., science as taught in schools) differs both from real science and from everyday life, although it shares some characteristics of each. Thus it has goals and corresponding cognitive methods of its own—and these differ from those of real science. As a result, students' learning difficulties may be compounded because real scientific goals are distorted and scientific ways of thinking are inadequately taught.

Our aim in presenting this analysis is to point out important cognitive issues which, with some exceptions (e.g., Schoenfeld, 1983, 1987), have in the past rarely been examined; to provide a framework for studying such issues; to indicate evidence that these issues are important for science education; and to suggest empirical investigations and instructional approaches for pursuing these issues in greater depth.

Kinds of Knowledge in a Domain

A knowledge domain is the collection of declarative and procedural knowledge useful for attaining some particular goals. (Examples are the knowledge domains of physics or of everyday life.) The following paragraphs discuss the kinds of knowledge important in any such domain and point out how inadequacies in such knowledge can lead to learning difficulties when encountering a previously unfamiliar domain.

Specific domain knowledge. The specific knowledge of a domain is obviously important. It consists of the concepts used in this domain, the relations among them, and the methods for dealing with them. For example, specific knowledge of physics consists of the concepts, principles, and methods useful in physics. Similarly, specific everyday knowledge consists of the factual knowledge and methods useful for coping with daily life.

As indicated in the black-bordered box in Figure 1, the specific domain knowledge includes also specifications of how the concepts are connected to the observations which they are ultimately intended to describe. (The domain of pure mathematics is exceptional since it is purely conceptual and symbolic, and thus does not explicitly refer to any observations.)

The specific domain knowledge, especially outside the realm of science, may not be entirely conscious and thus not always expressible in explicit form.

As indicated in Figure 1, the specific domain knowledge is based on the goals of the domain and on the cognition useful in that domain. This cognition, which is also

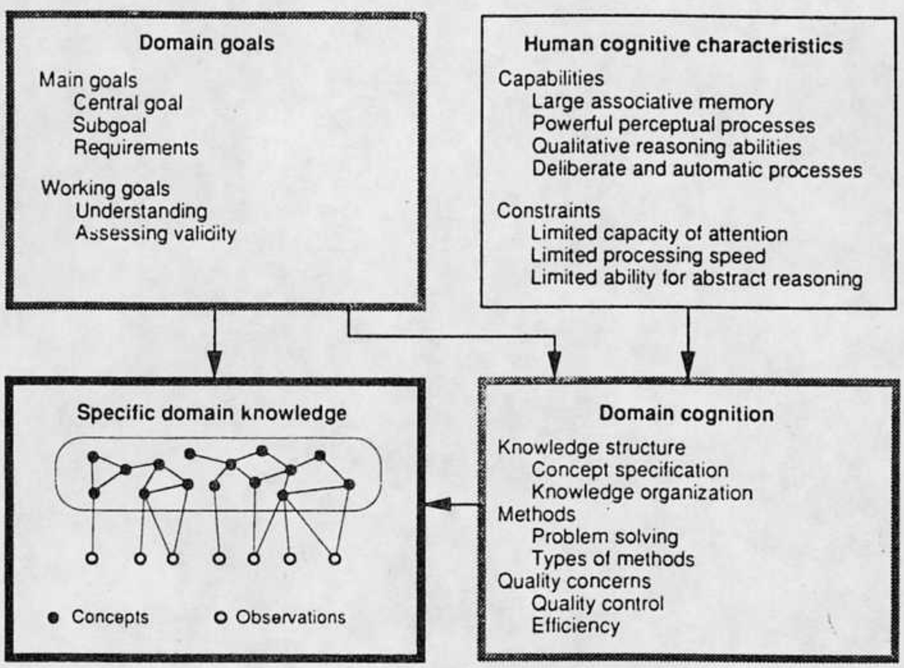

Figure 1. Important aspects of a knowledge domain.

influenced by the goals of the domain, is further constrained by general human cognitive characteristics. The following paragraphs comment on these aspects of the domain.

Domain goals. The goals of a domain affect crucially both the nature of the specific domain knowledge and the cognition useful in the domain. (For example, the central goal of science is to explain and predict observable phenomena. Correspondingly, specific scientific knowledge and scientific cognition are specially devised to achieve these goals.) The central goal of the domain imposes corresponding requirements on the knowledge required for its attainment. (For example, the goal of achieving great predictive power can only be attained if knowledge is adequately general and precise.) The central goal also influences working goals commonly pursued in the domain, e.g., achieving understanding and assessing validity.

Human cognitive characteristics. Because the intellectual tasks in a domain are predominantly performed by people, human cognitive capabilities and limitations constrain the kinds of cognitive processes usable in the domain. The capabilities and limitations of special interest in our discussion are listed in Figure 1 and will be discussed more fully later.

Domain cognition. The goals of a domain and the characteristics of human cognition jointly determine the cognitive means particularly useful in this domain. For example, to attain the scientific predictive and explanatory goals, scientists, subject to the limitations of human cognition, have devised special forms of knowledge and special methods to ensure effective, efficient, and error-free performance. In the words of the molecular biologist François Jacob (1988, p. 306): "The world of science, like that of art or religion, was a world created by the human imagination, but within very strict constraints imposed both by nature and the human brain."

Metaknowledge. Knowledge of the goals and useful cognition in a domain (summarized in the gray-bordered boxes in Figure 1) can be called "metaknowledge," because it is higher-level knowledge *about* more specific domain knowledge.[1]

The possession of such metaknowledge can markedly affect people's performance in the domain. Thus people's metaknowledge of the goals of a domain can crucially determine whether they pursue appropriate goals and heed the requirements needed to attain them. Similarly, their metaknowledge of the cognition useful in this domain can crucially determine whether they use appropriate cognitive strategies in this domain. For example, proficient work in physics requires not only specific knowledge of the principles and methods of physics; it also requires general knowledge of the goals of physics and of the ways of thinking useful in this domain.

In trying to deal with a previously unfamiliar knowledge domain, it is thus necessary not only to learn the specific knowledge of the new domain, but also the requisite metaknowledge. Indeed, deficiencies in such metaknowledge can lead to pervasive learning difficulties.

In the next two sections we shall analyze and compare in greater detail the domain goals and domain cognition of the everyday and scientific knowledge domains, and point out some of the resulting learning difficulties. (By everyday knowledge we mean common knowledge, about natural phenomena, acquired by most people in daily life and in early schooling before coming to a more systematic study of science. By

[1] *Metaknowledge* of the goals and cognition of a domain is distinct from an individual's *metacognitive* knowledge of his or her own cognitive processes.

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Our analysis will spec
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scientific domains. The last
to suggest some empirical

Domain goals
Main goals
Central goal
Subgoal
Requirements
Working goals
Understanding
Assessing validity

Domain cognition
Knowledge structure
Concept specification
Knowledge organization
Methods
Problem solving
Types of methods
Quality concerns
Quality control
Efficiency

Figure 2. Schematic

scientific knowledge we mean predominantly that encompassed by present-day physical sciences.)

Our analysis will specifically focus on the kinds of metaknowledge indicated in the gray-bordered boxes of Figure 1 and also listed in the left column of Figure 2. The other columns in this latter figure provide a schematic overview of this analysis by indicating the main characteristics of this metaknowledge in the everyday and scientific domains. The last section of the article will build on this comparative analysis to suggest some empirical investigations and instructional recommendations.

	Everyday domain	Scientific domain
Domain goals		
Main goals		
Central goal	Leading a good life	Optimal prediction and explanation
Subgoal	Adequate prediction and explanation	
Requirements	Adequate generality, parsimony, precision, consistency	Maximal generality, parsimony, precision, consistency
Working goals		
Understanding	Few inferences Various acceptable premises	Many inferences Well-specified premises
Assessing validity	Moderate importance Various acceptable premises Plausible inference rules	Central importance Observation-based premises Well-specified inference rules
Domain cognition		
Knowledge structure		
Concept specification	Implicit and schema-based	Explicit and rule-based
Knowledge organization	Locally coherent Associative organization	Globally coherent Logical organization
Methods		
Problem solving	Short inferences based on rich compiled knowledge	Long inferences based on parsimonious knowledge
Types of methods	Non-formal	Complementary formal and non-formal
Quality concerns		
Quality control	Non-formal	Strict and explicit
Efficiency	Naturally efficient for everyday tasks	Designed for efficiency in complex tasks

Figure 2. Schematic comparison of everyday and scientific knowledge domains.

Goals of Everyday and Scientific Domains

This section examines and compares the differing main goals of everyday life and of science, and the working goals pursued to achieve understanding and assess validity.

Main Goals

Central Goals and Subgoals

Implicit everyday goals. The goals of everyday life are largely implicit and not sharply defined. Roughly, the central goal is to lead a satisfying life. In the service of this goal, it is necessary to cope satisfactorily with one's environment. Thus it is important to pursue the subgoal of predicting, and sometimes explaining, commonly observed physical and biological phenomena. For example, it is useful to predict that a parked car will roll downhill if its brakes fail, or to explain why pressing a switch does not produce the expected light from a lamp.

Explicit scientific goals. In the domain of science, this implicit subgoal of everyday life is elevated to become the explicit central goal to be pursued to the best possible extent. Thus the central goal of science is to achieve *optimal* prediction and explanation by devising special theoretical knowledge which parsimoniously (i.e., on the basis of a minimum number of premises) permits inferences about the largest possible number of observable phenomena. In the words of Einstein (1954, p. 293) "The aim of science is, on the one hand, a comprehension, as complete as possible, of the connection between the sense experiences in their totality, and, on the other hand, the accomplishment of this aim by the use of a minimum of primary concepts and relations."

Requirements

Limited everyday requirements. The requirements needed for achieving adequate everyday prediction or explanation are not too stringent. (a) Various kinds of knowledge can be used as appropriate in different contexts, without requiring great generality or needing global consistency. Thus one can efficiently use large amounts of context-specific knowledge (based on daily experience, common sense, or tradition) without having to make extensive or explicit inferences. (b) The requisite knowledge rarely needs to be unduly precise. Some ambiguities and vagueness are tolerable, and can usually be adequately resolved by refinements or discussions in specific contexts. (c) Long accurate inference chains are rarely required, although some kinds of moderately long inferences [e.g., working backwards with successive subgoals (Klahr, 1978)] can be readily handled.

Stringent scientific requirements. Attainment of the scientific goal of optimal prediction and explanation imposes very stringent requirements. (a) There is a need for great generality, and correspondingly long inference chains, to ensure that a very small number of theoretical premises can lead to predictions about very many phenomena. (b) Consistency must be maintained throughout the entire scientific knowledge structure to guarantee that different arguments do not lead to contradictory predictions. (c) All scientific knowledge needs to be precisely specified so that unambiguous predictions can be made to any desired degree of precision. The following paragraphs elaborate some consequences of these requirements.

1. Focus on inferences. The central scientific goal implies less interest in mere factual knowledge than in the ability to make the inferences needed for prediction or

explanation. In the words of the physicist William Bragg, "The important thing in science is not so much to obtain new facts as to discover new ways of thinking about them."

2. Deliberate construction of knowledge. Scientific knowledge is deliberately constructed and refined to achieve optimal explanatory and predictive power. As Einstein said (1954, p. 323), "Science is the attempt to make the chaotic diversity of our sense-experience correspond to a logically uniform system of thought." Even more explicitly, he states (Holton, 1988, p. 251): "We are concerned with the eternal antithesis between the two inseparable components of our knowledge, the empirical and the rational . . . The structure of the system is the work of reason; the empirical contents and their mutual relations must find their representation in the conclusions of the theory. In the possibility of such a representation lie the sole value and justification of the whole system and especially the concepts and fundamental principles which underlie it. Apart from that, the latter are free inventions of the human intellect, which cannot be justified either by the nature of that intellect or in any other fashion a priori."

Correspondingly, scientific knowledge is never absolutely true, but a theoretical construct to be constantly refined. Thus Einstein (1954, p. 323) speaks of scientific ideas as "man-made," "the result of an extremely laborious process of adaptation," and thus also "hypothetical, never completely final, always subject to question and doubt." The ethologist Konrad Lorenz states similarly: "Truth in science can be defined as the working hypothesis best suited to open the way to the next better one." Scientific knowledge is thus the result of a continual process of progressive refinement where scientific theories of limited validity are often used as stepping stones to more general and precise theories.

3. Need to transcend existing knowledge. Systematic pursuit of the scientific goals implies the need to transcend existing conceptions. Thus seemingly obvious commonsense notions often need to be abandoned in favor of new concepts deliberately invented to predict and explain phenomena far more extensive than those encountered in everyday life. For example, one may need to realize that the time between two events is different for different observers (relativity theory), or that it is meaningless to talk about the path of an atomic particle (quantum theory). Indeed, contemporary elementary-particle physics is characterized by great freedom of theoretical invention totally unconstrained by everyday common sense. Bridgman (1955, p. 81) observed: "[The working scientist] feels complete freedom to utilize any method or device which in the particular situation before him seems likely to yield the correct answer. In his attack on the specific problem he suffers no inhibitions of precedent or authority, but is completely free to adopt any course that his ingenuity is capable of suggesting to him."

There is also a need to transcend traditional beliefs or the opinions of authority figures—sometimes even those of great scientists. As Richard Feynman is reputed to have said, "Science is the belief in the ignorance of experts." For example, in 1959 Josephson, then a lowly graduate student, predicted the possibility of a superconducting current between two closely spaced superconducting metals. At that time the famous physicist John Bardeen, father of the superconductivity theory, expressed strong disbelief. Yet the predicted effect was looked for and observed—and resulted in the award of a Nobel prize to Josephson.

Increasing gap between scientific and everyday domains. "The whole of science is nothing more than a refinement of everyday thinking." This statement by Einstein (1954, p. 290) is certainly true. However, the refinement has been very substantial.

The central scientific goal of optimal prediction and explanation is a very ambitious extension of the more modest predictive and explanatory goals of everyday life, and thus imposes much more stringent requirements. Furthermore, scientific advances over several centuries have led to scientific knowledge that has become increasingly more voluminous, more precise, more abstract and highly symbolic, and more prone to deal with phenomena and concepts never encountered in everyday life (e.g., atomic particles, genes, speeds close to that of light, etc.). As a result, the gap between scientific knowledge and that of everyday life has become increasingly large.

Learning Implications

Not surprisingly, students tend to import everyday goal conceptions into the scientific domain—with the result that they often pursue inappropriate goals in their study of science. Thus most students do not share scientists' focus on making inferences and transcending existing knowledge.

Focus on factual knowledge. Many students view scientific knowledge predominantly as a valuable collection of facts and formulas, rather than as a conceptual structure enabling numerous predictions. Hence they strive primarily to memorize various scientific facts and formulas, rather than to learn a few basic principles and reasoning methods enabling many diverse inferences. Similarly, they often focus on learning the solutions of standard problems, rather than the thought methods needed to solve unfamiliar problems. Such learning goals have far-reaching implications because they lead students to acquire inert knowledge which is not flexibly usable.

Acceptance of existing knowledge. Students tend to accept commonsense notions. They find it difficult to believe that these may be scientifically meaningless or not useful (e.g., motion or time specified without a reference frame). Conversely, they have difficulties appreciating that artificially invented concepts (e.g., angular momentum, electric capacitance, etc.) can be highly meaningful and useful.

Similarly, students are prone to accept uncritically knowledge acquired from authoritative sources, such as teachers or textbooks, even if they are unable to interpret it properly or connect it to observations. For example, many students claim that it is not true that the sun moves relative to the earth (despite their own observations to the contrary) because they learned in school that it is really the earth that moves around the sun. Thus the students are quite prepared to accept the authority of teachers, and of scientists like Copernicus or Galileo, without understanding the relativity of motion and the observational implications.

Furthermore, students often bring with them everyday notions of absolute truth and naive notions that science provides such truth. Thus they find it sometimes difficult to accept that scientific theories are modifiable and improvable, that science is not necessarily exact, that it may be useful to work with approximate scientific theories, and that one may want to make approximations even if precise theories are available (see, for example, Songer & Linn, 1991).

Role of School Science

Science courses taught in schools often tend to reinforce students' goal conceptions and thus to focus on goals significantly different from those of real science. (a) Examinations and grading policies often reward the memorization of factual knowledge

and formulas, rather than the ability to use of such knowledge flexibly. (b) Textbooks commonly emphasize mathematical formulas, sometimes to the extent of displaying laundry lists of such formulas (e.g., Ohanian, 1985, p. 563). (c) Goals in the school environment are largely focused on satisfying criteria specified by teachers, textbooks, examinations, and other legitimated sources of authority. But, unlike in science or everyday life, these criteria are often only remotely connected to directly observable natural phenomena.

Working Goals

In the service of the main goals indicated in Figure 2, a knowledge domain requires routine pursuit of some important working goals, especially those of achieving understanding and assessing validity. But the criteria for determining understanding or validity, and the methods for attaining them, differ significantly in everyday life and in science.

Understanding

Everyday understanding. Knowledge in everyday life is ordinarily not deliberately sought, but spontaneously acquired through interaction with the world and other people. Thus people sometimes say that they understand something merely because they have experience with it. They may also say that they understand aspects of the world if they can explain or predict them sufficiently well so that they can make sense of them and interact with them satisfactorily. Past experience, and local knowledge about specific contexts, are generally quite adequate for such commonly needed predictions and explanations. (For example, a rough idea that an electric lamp requires an uninterrupted electric path is enough to understand why a lamp might malfunction and to suggest checking whether it is plugged in, whether the bulb is tight, and whether the cord is undamaged.)

There are no well-defined critera of what constitutes understanding in everyday life. In particular, there are no requirements for inference chains based on well-specified premises and inference rules. Thus people may claim that they understand something because they can relate it, by reasonable arguments, to common sense or other familiar knowledge. Similarly, understanding may be demonstrated by explanations that merely identify a perceived causative agent or note some connections among relevant features. Such explanations are not only common among children (Metz, 1991), but also among adults.

As illustrated by the previous example of the lamp, such understanding is sufficient for most everyday situations. Indeed, striving for what scientists call understanding requires motivation beyond satisfactory everyday functioning.

Scientific understanding. By contrast, understanding in science is a working goal pursued deliberately in the service of the central goal of explaining and predicting parsimoniously as many observable phenomena as possible. Indeed, deliberate efforts are often undertaken to test the limits of scientific understanding—and to extend such understanding if it is found to be deficient.

The criteria of scientific understanding are well specified. (a) Understanding is to be demonstrated by the ability to make many diverse inferences—either predictions which involve inferences from basic premises to observable phenomena, or explanations

which involve inferences showing how observable phenomena can be deduced from basic premises. (b) Scientific understanding is never absolute, but a comparative notion. Thus understanding is said to be greater to the extent that one is able to predict and explain a larger range of diverse phenomena on the basis of fewer premises. (c) The basic premises are the well-specified postulates of some theory, and reasoning from these postulates is to be achieved by the inference rules of deductive logic. (d) The requirement of parsimonious predictions or explanations implies that demonstration of understanding may involve long inference chains from only a few basic premises.

Different theoretical premises may be used as the basis of understanding—depending on what is possible or desirable. For example, one may understand the properties of a gas on the basis of the macroscopic premises of a thermodynamic theory—or one may also understand it in greater detail (with greater predictive and explanatory power, albeit at the expense of more complex inferences) on the basis of more detailed atomic theories and statistical concepts.

The theoretical premises used as the basis of understanding may be very abstract and remote from any commonsense notions. For example, the yellow color of sodium lamps may be understood scientifically on the basis of very abstract premises of quantum mechanics and electromagnetic theory.

Validity

Everyday validity. In everyday life the usual assumption is that knowledge is valid and trustworthy unless there are strong indications to believe otherwise. Thus there is ordinarily no strongly perceived need to check knowledge for its validity.

The notion of validity in everyday life is not sharply defined and the criteria for determining validity are not explicitly specified. When validity needs to be assessed (e.g., when it is questioned by someone else), usual arguments advanced in favor of validity are in consonance with past observations, with common sense, or with other reasonable knowledge. Other bases for validity include support from tradition, social groups, or respected authorities.

Scientific validity. By contrast, assessing the validity of scientific knowledge is a crucially important goal, persistently pursued to achieve the central scientific goal of effective prediction and explanation. Validity needs to be carefully checked to ensure that inferences from basic premises are free from errors and unwarranted conclusions—and thus also to ensure the correctness and consistency of the entire body of scientific knowledge. Furthermore, discrepancies discovered by attempts at validation help reveal deficiencies of existing scientific knowledge and indicate where modifications need to be made.

The highly perceived need to check validity motivates deliberate checking of observations by replicating experiments and obtaining converging lines of evidence. It also leads to the habitual use of explicitly justified arguments or formal proofs to ensure that inferences are valid and to convince others of their validity.

The criteria of scientific validity are well specified. Ultimately, the criteria are agreement with observations. Secondarily, they are agreement with inferences based on well-established theoretical premises, accepted because of their power to predict and explain a large range of observations. In this second case the criteria of validity coincide then with those of scientific explanation, i.e., an assertion is judged valid because it can be explained on the basis of well-established scientific premises.

Learning Implications

The preceding comparative comments lead to the expectation that students will import everyday conceptions of understanding and validity into the scientific realm where such conceptions are naive or inadequate. The following are some examples.

Familiarity as criterion of understanding. Because everyday understanding is usually acquired through experience and implicit learning, students often use familiarity as a criterion for understanding—rather than the scientific criterion which requires demonstrating the ability to make many diverse inferences. Thus they may claim that they understand Newton's basic mechanics principle ($\mathbf{F} = m\mathbf{a}$) because they can state it and have studied it—although they may have little ability to apply it to solve various problems. For example, when getting a bad grade on a test where they failed to solve pertinent problems based on this principle, they feel aggrieved and upset because they believe that (on the basis of their everyday notion of understanding) they nonetheless really "understand" the principle.

Acceptability of scientifically ill-founded explanations. Students often use everday reasoning (direct perception and common sense) to advance explanations which lack a basis in scientific premises. For example, it may seem sensible that a moving particle emerging from a curved tube continues for a while in a curved path; or that an object moves in the direction of the force applied to it; or that some characteristics acquired during an animal's life are transmitted to its offspring. Students not uncommonly advance explanations based on such plausible arguments even after taking science courses where they ostensibly learned scientific principles whose application would lead to quite different conclusions. Usual teaching methods have thus only limited effectiveness in conveying to students the requirements of scientific explanation.

Unacceptability of scientifically well-founded explanations. Because formally correct scientific explanations may not seem "sensible" or in accord with everyday criteria of explanation, students sometimes find them unsatisfactory. For example, when air resistance is negligible, a projectile moves with constant horizontal velocity. The reason, according to Newton's laws of mechanics, is that no horizontal force acts on it. But some students find this explanation unsatisfactory because it fails to meet the everyday requirements of an explanation consonant with commonsense notions. They find it even harder to accept explanations based on the more abstract laws of quantum mechanics.

Consequences for learning. Students' conceptions of understanding have far-reaching implications for their learning. (a) Such conceptions determine students' learning goals and how they focus their attention. (b) They also determine when students are satisfied with their own learning and cease further efforts.

Hence students' everyday conceptions of understanding greatly affect what they learn in science and how well they learn it. In particular, many students do not aim at the scientific goal of understanding, as demonstrated by the ability to make extensive inferences. As a result, they often acquire scientific knowledge which is inert rather than flexibly usable.

Consequences of conceptions of validity. Students, coming from everyday life into science, often perceive little need for explicit validation of the kind used in science, e.g., little need to justify steps of an argument in terms of basic scientific premises. Furthermore, lacking clear criteria of scientific explanation, they are also prone to claim validity on the basis of ill-specified nonscientific criteria, such as conformity with common sense or intuition.

concept specifications can usually be adequately resolved by relying on successive approximations and interpersonal communication.

Everyday concepts are most often learned without explicit effort. For example, when automatic teller machines became common, few of us explicitly pursued the goal of learning the defining attributes of these devices.

Scientific concept specification. By contrast, the scientific goal of parsimonious and extensive predictive power imposes exacting requirements on scientific concepts. (a) Such concepts must be precisely defined and should lead to no inconsistencies. (b) Within these constraints, scientific concepts may be freely invented if that seems useful, without regard to common sense or other preconceptions. In Einstein's words (1954, p. 13), "All concepts, even those which are closest to experience, are from the point of view of logic freely chosen conventions." (c) Many scientific concepts (e.g., magnetic field, wave function, gene, . . .) need to be very general to permit parsimonious predictions. But despite their generality, they must be unambiguously interpretable in any specific instance, even if the reasoning chain is long and indirect. (d) All concepts must ultimately be connected to observations; otherwise they are scientifically meaningless since they are irrelevant to the central scientific goal of predicting and explaining observable phenomena. Again, in Einstein's words (1954, p. 291): "Concepts and relations, and indeed the postulation of real objects and, generally speaking, of the existence of 'the real world', have justification only in so far as they are connected with sense impressions between which they form a mental connection."

To achieve the preceding requirements, scientific concepts must be explicitly defined to specify unambiguous connections to their referents—and ultimately to observable phenomena. The concepts may specify either entities (particular entities like the "sun," or generic entities like "particle" or "triangle") or properties associated with them (e.g., "mass," "acceleration," etc.). The connection between a concept and observations can be made most explicit by a formal operational definition which specifies what one must actually *do* to determine the value (including category membership) of the concept in any particular situation. Less precisely specified recognition processes may be used to identify familiar scientific concepts efficiently; but such concept identifications must be consistent with formal definitions (Reif, 1987a).

Knowledge Organization

Everyday knowledge organization. Everyday knowledge consists of interrelated concepts forming a large network of associated knowledge elements. (a) New knowledge is acquired automatically through experience and stored together with information reflecting its acquisition context, but without any global integration. (b) The resulting knowledge may be only locally coherent, i.e., inferences may only be possible among closely associated knowledge elements and contradictions may occur. But local coherence is sufficient to ensure adequate consistency of the knowledge in specific contexts. (c) Relevant knowledge elements can be adequately retrieved in response to cues provided by various contexts.

Scientific knowledge organization. Knowledge in science must be organized so as to facilitate the central goal of making extensive inferences on the basis of very few basic premises. (a) Accordingly, scientific knowledge must be highly coherent, i.e., it must allow many knowledge elements to be inferred from only very few. Such coherence also ensures the global consistency of the entire knowledge structure. (b)

The knowledge must be organized so that the logical relationships between knowledge elements are highly explicit. For example, hierarchical forms of organization are useful for effective classification, and also facilitate deductive inferences from a few general premises to more numerous detailed results. (Such organization is superimposed on the associative memory structure and can coexist with other nonlogical associations among knowledge elements.)

Coherence and logical organization facilitate the following cognitive processes important in science (Eylon & Reif, 1984): (a) Remembering accurately much knowledge, and regenerating it if partially forgotten. (b) Avoiding inconsistencies and contradictions. (c) Extending the knowledge—because the knowledge structure assists deductions, suggests plausible inferences, and can often incorporate new knowledge into a preexisting logical structure.

Such advantages are achieved by taxonomic classification schemes, like those used in biology, and even to a greater extent by the highly coherent logical knowledge organizations prevalent in the physical sciences. For example, all of classical mechanics is deductively based on Newton's three laws of mechanics, and all electric and magnetic phenomena (including radio waves and optics) can be largely understood on the basis of Maxwell's four fundamental equations of electromagnetism.

Learning Implications

Coming to science from everyday life, many students do not perceive the need for unambiguous concept specifications—nor do they have experience with the formal thinking required to achieve such specifications. Similarly, they do not fully perceive the need for organizing their newly acquired scientific knowledge so that it is globally coherent and logically consistent—nor is it easy for them to do this. As a result, students often transfer into the scientific domain informal concept-specification methods and predominantly associative knowledge organizations which are efficient in everyday life, but inadequate in science.

Inadequately specified concepts. The following are some examples: (a) Students in science courses often feel free to use special words, like "energy" or "momentum," without attaching clear scientific meanings to them. (b) They learn to identify and recognize various scientific concepts (e.g., "component of a vector," "resistors in parallel," etc.) by visual comparison with prototypical cases. But they often cannot specify these concepts explicitly and thus are unable to identify them properly in atypical situations (Reif, 1987a). (c) Although they may be able to state the definitions of scientific concepts (e.g., of "acceleration"), they often do not know what to do to apply these definitions in specific cases (Labudde, Reif, & Quinn, 1988; Reif & Allen, in press).

Incoherent knowledge. Furthermore, students' knowledge of scientific concepts and principles is often fragmented (diSessa, 1988). For example, even college students often exhibit incoherent knowledge about so elementary a concept as "area." They commonly know various formulas for the areas of simple geometric figures, such as rectangles, triangles, and circles; but they often cannot state a general definition of area, nor use it to derive their formulas if need be.

Similarly, students often recall various bits of knowledge about the acceleration of a particle, e.g., formulas for the acceleration of a particle moving around a circle. But their knowledge is incoherent, often faulty because of neglected applicability

conditions, and not testable by checking it against a basic definition (Reif & Allen, in press). As a result, students are frequently led to inconsistencies that they cannot resolve. (For instance, they may not know whether to claim that the acceleration of a vertically thrown ball at its highest point is zero because its velocity is zero, or is nonzero because the direction of its velocity is changing.)

Because students' acquired scientific knowledge lacks coherence, it is difficult for them to learn and remember. For example, students often complain that there are so many formulas to remember in physics. By contrast, physicists, because their knowledge is coherent and well organized, often proudly proclaim that the great beauty of physics (unlike organic chemistry, for example) is that there is so little to remember.

Role of School Science

Science courses commonly teach many scientific terms. But even when concepts are adequately specified by definitional statements, the methods needed to interpret these statements in specific cases are rarely explicitly taught or practiced by students. As a result, students are often left with concepts that they are unable to interpret reliably (e.g., Halloun & Hestenes, 1985a; McDermott, 1984; Reif & Allen, in press).

Science courses in schools certainly place some emphasis on logical structure. But they commonly focus more on the content of the conveyed knowledge rather than its organization—especially, its organization in students' minds rather than merely in lectures or textbooks. Furthermore, an emphasis on formulas often obscures general ideas which would make students' knowledge more coherent. For example, formulas like $\mathbf{F} = m\mathbf{a}$ may well be memorized without acquiring general insights about the close relation between motion and interaction.

Methods

The need for making inferences to solve problems is pervasive, in everyday life as well as in science. It arises whenever one wants to attain some goal and needs to devise a sequence of actions leading to this goal.

The main difficulty of problem solving is the need to make judicious decisions so as to choose, among very many possible actions, the particular action sequence (or one of the very few such sequences) which leads to the desired goal. Thus one needs effective methods for making judicious decisions—and, as a prerequisite, also effective methods for describing problems in a way which makes apparent the potentially promising actions among which one may choose. Lastly, it requires methods for implementing all the actions which have been chosen.

Because of the scientific goal of making extensive and precise predictions on the basis of very few premises, the inference chains required to solve scientific problems need ordinarily to be much longer and reliably accurate than those required to solve everyday problems. The methods required to cope with scientific problems need thus be correspondingly more refined.

Everyday Domain

Everyday problems can often be solved by relying on large amounts of accumulated knowledge and by using this knowledge to make relatively short inferences in particular

contexts. The required methods can often rely heavily on perceptual processes, pattern recognition, and qualitative reasoning. These methods are highly efficient and are usually sufficient to attain everyday goals with adequate precision and consistency. For example, the problem of assembling a coffee maker to brew coffee, although quite complex, is readily solved by qualitative reasoning exploiting visual cues provided by objects in the environment (Larkin, 1989).

Scientific Domain

Although such methods are also useful in science, alone they are inadequate to attain scientific goals. (a) They are usually not sufficient to achieve the unambiguity and precision desired for scientific work, nor to ensure the global consistency of scientific knowledge. (b) Above all, they are ill suited to make the long inference chains needed to achieve wide-ranging predictions on the basis of very few premises.

Formal methods. Accordingly, scientists have increasingly invented formal methods deliberately designed to implement long inference chains with great precision. Such methods attempt to augment human cognitive capabilities by devising special symbolic representations, and explicit rules and procedures for working with them. Examples include many kinds of mathematical formalisms (such as algebra, calculus, vector analysis, etc.); they also include structural formulas in organic chemistry, and special symbolisms to deal with genetic analyses and metabolic pathways in biology.

Such formal methods, involving precise rule-based reasoning, are not naturally congenial to humans (Johnson-Laird, 1983), are difficult to learn, and require specialized training. Furthermore, formal methods require delicate abilities to interpret abstract symbols appropriately in any particular concrete instance.

Nonformal methods. Formal methods are by no means sufficient for all scientific tasks. In particular, they are not especially well suited to make the decisions needed to facilitate search, e.g., to plan problem solutions, formulate subproblems useful for their solution, design experiments, suggest possible mechanisms for observed effects, devise new theories, etc. Such search tasks are very important; moreover, even approximate results can be very useful in narrowing the domain of search and providing springboards for further refinement. To deal with such tasks in science, it is helpful to resort to nonformal methods that exploit human perceptual processes and qualitative reasoning capabilities. These nonformal methods are similar to those used in everyday life, but not identical. Thus they are deliberately devised to be consistent with formal methods, need not correspond to everyday intuitions, and may be far removed from common sense.

Examples of such nonformal methods include verbal reasoning and the use of visual representations that exploit human perceptual processes. Some of these representations may be diagrams or pictures closely corresponding to direct perceptions of the physical world (e.g., diagrams of pulleys or of biological cells). But others may represent highly abstract concepts far removed from the observations which they are designed to describe (e.g., graphs of speed versus time, arrows representing the amplitudes and phases of waves, diagrams indicating equilibrium temperatures and pressures for solid, liquid, and gaseous phases of a substance, etc.). In addition, simple mental models are often used in conjunction with such visual representations to reason qualitatively about complex mechanisms (such as electric resistance, scattering or absorption of light by molecules, etc.).

Complementary use of formal and nonformal methods. To deal effectively and efficiently with the task demands of science, scientists use formal and nonformal methods jointly in complementary ways. Thus they can achieve precise extensive inferences, as well as flexible creativity.

For example, rigorous statistical analyses of data may often need to be supplemented by nonformal graphical representations to make the results interpretable (Tufte, 1983, 1990). Similarly, the analysis of many complex phenomena (e.g., nonlinear mechanics, chaos, meteorology, etc.) requires not only the solution of nonlinear differential equations, but careful attention to visual representations or computer displays which can make the results of such analyses comprehensible.

Even theoretical physicists, who deal with the most mathematically formal aspects of science, express the need for nonformal methods. For example, Einstein writes (Hadamard, 1945): "The words of the language . . . do not seem to play any role in my mechanisms of thought. The psychical entities which seem to serve as elements of thought are certain signs and more or less clear images which can be 'voluntarily' reproduced and combined . . . before there is any connection with logical construction in words or other kinds of signs." Similarly, Feynman, in his 1965 Nobel-prize lecture, states (Feynman, 1966, p. 44; also, Schwinger, 1989, p. 48): "Physical reasoning does help some people to generate suggestions as to how the unknown may be related to the known. Theories of the known, which are described by different physical ideas, may be equivalent in all their predictions and are hence scientifically indistinguishable. However, they are not psychologically identical when trying to move from that base into the unknown." As another example, Bethe describes Fermi's thinking in these words (Bernstein, 1979): "From Fermi I learned . . . to look at things qualitatively first and understand the problem physically before putting a lot of formulas on paper . . . Fermi was as much an experimenter as a theorist, and the mathematical solution was for him more a confirmation of his understanding of a problem than the basis of it."

Such complementary use of both formal and nonformal methods represents a highly sophisticated and effective approach for dealing with complex problem-solving tasks in science.

Learning Implications

Ineffective use of everyday problem-solving approaches. Students commonly import into science problem-solving strategies used in everyday life, where inference chains are shorter because of greater reliance on accumulated context-specific knowledge. Thus students, approaching the study of science, often try to accumulate a stockpile of prototypical problem solutions which they hope to use as starting points for other problems that they might encounter. Furthermore, instead of learning general decision strategies, they tend to focus narrowly on various specific equations—and thus often fail to see the woods because they get lost among the trees. Such problem-solving approaches are often inadequate to deal even with relatively simple problems encountered in introductory science courses.

Inappropriate reliance on either formal or non-formal methods. Having no everyday experience with formal methods, many students use them inappropriately, either relying excessively on these symbolic methods or on nonformal methods, but not realizing the need to use such methods jointly in complementary ways.

Often students perceive no need for formal methods, or find such methods difficult to implement, but instead use nonformal methods from daily life. For example, they often answer questions about the motion of objects, or forces on them, on the basis of what seems sensible—without any formal reasoning based on Newton's basic mechanics principle (**F** = *m***a**) which they have learned.

On the other hand, many students rely excessively on the formal methods which they have been taught, believing that these are the essence of science. Yet, they often cannot interpret the symbolism appropriately in concrete situations, and thus end up applying symbols mindlessly without using less formal thinking as a guide or check. For example, students may solve a problem by resorting to algebraic equations, but fail to visualize the situation and thus not realize that the problem makes no sense (Paige & Simon, 1966). Similarly, when asked how many buses are required to transport 1128 soldiers if each bus holds 36 people, about half the students in a national assessment engaged in long division to arrive at nonsensical answers such as "31 remainder 12", or as "31" obtained by mindlessly rounding off this result (Carpenter, Lindquist, Matthews, & Silver, 1983).

Excessive reliance on formal methods may persist well into graduate school. For example, graduate students in physics learn much formal physics knowledge about classical and quantum mechanics, electromagnetic theory, statistical mechanics, etc. Yet many of these student discover that such formal knowledge and ways of thinking are quite insufficient when they come to do research, and that they also need to learn the nonformal methods used effectively by experienced physicists.

Role of School Science

Problem-solving instruction. Problem solving is ordinarily taught in science courses by presenting some pertinent scientific concepts and principles, showing examples of some typical problem solutions, and giving students practice in solving similar problems. This instructional approach, which does not teach problem-solving methods explicitly, has the following limitations: (a) The solution examples reveal little about the thought *processes* needed to generate them, e.g., about how to make judicious decisions, how to avoid dead ends, and how to recover from impasses. Yet the main problem-solving difficulty faced by students is precisely *how* to make such decisions. (b) Solution examples show a logical linear sequence of steps and thus suggest to students that the solution *process* should be equally linear. This is not true (no more than a computer program of 1000 lines of code is effectively constructed in linear order) and fails to teach more powerful methods of progressive refinement. (c) Although practice is certainly necessary for learning problem solving, students often spend much time floundering—thus practicing largely useless skills and poor methods. Indeed, as in athletics or musical instruction, practice that is not carefully designed may be useless or even harmful—leading to bad habits which are difficult to break.

Furthermore, when dealing with the time pressures imposed by school examinations and workloads, many students believe (with some justification) that they can cope better by memorizing standard results than by engaging in the longer reasoning processes needed for systematic problem solving.

There is evidence that school instruction is often far from effective in teaching the problem-solving methods needed in science. For example, we found (Heller & Reif, 1984) that Berkeley students who had completed a basic physics course with a

grade of B or better could solve correctly only about 35% of typical textbook physics problems of the kind repeatedly encountered in their course.

Excessive formality or informality. Science courses in schools rarely succeed in teaching the complementary formal and nonformal methods needed in science. Instead, they often emphasize unduly formal methods at the expense of more qualitative and meaningful understanding. As a result, many students learn to manipulate symbols and equations, to quote formal definitions or principles, and to memorize formal proofs. But they often cannot interpret their symbolic knowledge and are left unable to use their knowledge flexibly. At the other extreme, less rigorous courses tend to emphasize informal reasoning, without providing any sense of the powerful formal methods used to attain the demanding goals of science.

Quality Concerns

The mere availability of knowledge in any domain does not guarantee that it will be used well. Thus one needs to be concerned with appropriate *quality control*, i.e., with ensuring that available knowledge is used without errors and as well as reasonably possible. Furthermore, one needs to ensure not only that knowledge is used effectively, but *efficiently*, i.e., that tasks are performed without undue expenditure of time and mental effort. However, the criteria of good quality and efficiency, and the corresponding methods needed to ensure such quality and efficiency, differ in everyday and scientific domains.

Quality Control

Everyday domain. In everyday life, errors are usually well enough prevented and corrected by informal means, e.g., by noticing unsatisfactory results or by heeding comments from other people. Many errors are regarded as mere slips because they do not usually cause much trouble. Thus they are remedied if necessary, but usually not examined at greater length.

Scientific domain. By contrast, the scientific goal of achieving numerous consistent predictions imposes severe requirements on eliminating errors and other deficiencies (e.g., cumbersome or unclear reasoning). Furthermore, the goal of parsimony requires long inference chains from very few premises—and correspondingly presents many opportunities for errors. Finally, as noted earlier, human beings are particularly error prone when making inference chains involving abstract symbols.

Adequate quality control in science thus requires specially devised cognitive strategies. (a) There is an explicit recognition that humans (like all other complex functional systems) are expected to make errors—and that it is, therefore, essential to develop systematic methods for eliminating such errors. Such methods must include preventive methods designed to avoid errors—and remedial methods designed to detect, diagnose, and correct errors when they occur. (b) It is important to identify possible sources of error so that one can develop improved methods for dealing reliably with complex tasks and avoid erroneous conclusions. Hence substantial attention is devoted to understand the reasons for errors.

Deliberate quality-control methods devised for scientific work range from trivial to elaborate, as indicated by the following examples: (a) Symbols are carefully chosen to reduce cognitive load and to facilitate important discriminations. For instance,

standard symbols are conventionally used in all contexts (e.g., V for electric potential, $\mathbf{E}$ for electric field, etc.) and letters denoting vector quantities are consistently ornamented by boldface type or by arrows. (b) Significant attention is paid to the formats for presenting arguments or calculations (e.g., to the visual layout on a page of equations or computer code). (c) Steps in a calculation are carefully documented to help comprehension by oneself and others, and to facilitate future modifications. (d) Special methods are used to prevent bias or self-deception (e.g., automatic instrumentation or double-blind experiments). (e) Systematic procedures are used to check work by other scientists (e.g., replication of experiments and multiple reviews of articles submitted to scientific journals).

Efficiency

Everyday domain. Human cognition is naturally well adapted for the efficient accomplishment of everyday tasks which require only moderate precision and consistency. In particular, it is often possible to perform such tasks rapidly and effortlessly by relying on pattern-recognition processes and accumulated context-specific knowledge.

Scientific domain. By contrast, scientific work often requires long and complex inference chains. Accordingly, more deliberate attention to cognitive efficiency becomes important for several reasons: (a) Efficiency becomes intrinsically more significant for long tasks. (For instance, increased efficiency, which leads to a twofold decrease in the time required for a task, is much more significant for a task requiring months than for one requiring minutes.) (b) Complex tasks make demands which, without adequate efficiency, can easily transcend the limited human capacities of attention and processing speed. Indeed, if cognitive efficiency is too low, complex tasks may become totally unimplementable. (For example, one cannot write a complex computer program in assembly language because the enormous preoccupation with low-level details would leave too little mental capacity for attention to high-level design tasks, because the required time would exceed practical limits, and because the maintenance of accuracy would be nearly impossible.)

Hence there is a great need in science to devise methods of observation, of calculation, and of data analysis which are efficient to allow the performance of complex tasks. Furthermore, efficiency must be assessed by multiple criteria and by heeding long-term consequences. For example, documenting and continually checking calculations or computer programs is a time-consuming process; but it is efficient in the long run because it ultimately saves time that would otherwise be spent in detecting and correcting errors, struggling with needed modifications, and making the work comprehensible to others.

Learning Implications

Quality control. Students, accustomed to the informal methods of quality control used in daily life, commonly fail to appreciate how error prone humans tend to be, particularly when faced with exacting tasks requiring reliable correctness and precision. Similarly, when they make mistakes in invoking inapplicable principles or in erroneously elaborating pertinent principles, they often regard such errors as careless slips. Thus they see little reason to examine them with care so as to learn from them and to help avoid similar errors in the future.

Students rarely pose for themselves the explicit goal of devising deliberate methods of preventing and remedying errors. As a result, their methods of quality control remain often unsystematic. Furthermore, they see little need to implement even simple error-prevention methods taught to them (e.g., indicating units, distinguishing symbols denoting vectors from those denoting numbers, etc.).

Efficiency. Not surprisingly, students import from daily life plausible criteria of efficiency which may, however, turn out to be inefficient in more complex tasks where longer-term consequences need to be considered. The following are some examples: (a) Students often write out problem solutions without attention to good format of presentation on a page and without documented justification of solution steps—and then may get lost in a morass where they cannot identify relevant information. (b) They commonly skip intermediate steps in calculations (sometimes more than expert scientists would)—and then end up with mistaken results or long times looking for errors. (c) They spend very little time describing a problem carefully before trying to apply various equations—and then get stuck or make mistakes because they do not adequately understand the problem situation. (d) They learn newly encountered scientific concepts by memorizing their definitions, but deem it a waste of time to examine their implications in various special cases—and then get repeatedly stuck or confused when they need to apply these concepts in various problems.

Role of School Science

Science instruction in schools does emphasize correctness and penalizes students for mistakes on homeworks or examinations. However, in this setting students commonly come to view errors primarily as sources or embarrassment or punishment—rather than as potential sources of learning. Furthermore, systematic methods of preventing and correcting errors are rarely taught (except perhaps in computer-science courses where debugging methods are sometimes emphasized).

Science courses in schools also rarely instill in students a thoughtful concern for cognitive efficiency. Many exercises and problems given to students are very short compared to real scientific problems—and thus do not make prominent the need for cognitive efficiency. Furthermore, cramming for examinations (which often put a high premium on speed) encourages a concern with very short-term efficiency—rather than with the longer-term efficiency important in science.

Concluding Remarks

Summary

As discussed in the preceding pages, effective functioning in any domain requires not only specific knowledge about the domain, but also more general knowledge about the goals of the domain and the cognitive means for attaining them. Accordingly, it is of interest to analyze and compare the goals and cognition in the domains of everyday life and of science. We carried out such an analysis, summarized in Figures 1 and 2, by examining and comparing the central goals of these domains, and the subsidiary goals of understanding and assessing validity. We also examined and compared the cognition in these domains—their knowledge structures, the methods for using this knowledge, and ways of ensuring good quality of such use.

Our discussion led us to identify general learning difficulties expected when students come to the study of science from the domain of everyday life—and to point out examples of some commonly observed difficulties. Many of these difficulties arise because students do not adequately understand the goals of science, nor the kinds of cognitive processes needed to deal with this unfamiliar domain. Thus they import into the scientific domain goals or cognitive means well suited to everyday life, but inadequate in science—or devise cognitive means which are ill suited to science. These learning difficulties can be pervasive because they affect crucially how students focus their attention and approach the process of learning science.

Additional complications arise because the scientific knowledge taught in schools differs both from real science and from everyday life, although it shares some characteristics of each. As a result, students' learning difficulties are compounded because real scientific goals may be distorted and effective scientific ways of thinking may be inadequately taught.

Suggested Investigations

Except for various illustrative examples, our discussion was largely theoretical—designed to elucidate important issues, to provide an analytical framework, and to point the way to more detailed future investigations. The following kinds of investigations would be of particular interest:

Empirical investigations. (a) Systematic interviews would be useful to identify in greater detail students' conceptions of the goals of science and of the thought processes which they deem useful for science. For example, the work of Songer and Linn (1991) is a step in this direction, and indicates that students who have a more realistic perception of the nature of science also deal better with scientific subject matter. (b) To go beyond such verbal reports of students' conceptions, one could observe students' actual behavior. Thus it would be of interest to make comparative observations of individual students to ascertain how the same students approach cognitive tasks, like concept learning or problem solving, in everyday contexts and in scientific domains. (c) Last, it would be particularly interesting, although perhaps most difficult, to carry out experiments to investigate how more explicit specifications of learning goals, consonant with scientific goals, would affect students' learning behavior.

Transitions between other kinds of knowledge domains. Our interest has been specially focused on everyday knowledge and natural science. However, our analysis of different knowledge domains has been quite general in identifying the kinds of goals and of cognitive means important in any domain. Hence it would be illuminating to examine and compare similarly other knowledge domains (such as those of social science, the law, literary criticism, etc.) to elucidate some of their salient characteristics. Such an examination would also identify likely learning difficulties when students come to one of these domains from everyday life or from some other domain (e.g., to the study of social science from a previous background in natural science).

Instructional Implications

Prevailing instructional deficiencies. We already pointed out some of the deficiencies of prevailing science instruction in schools. Not only does such instruction rarely address the pervasive kinds of difficulties identified in the preceding pages, but

schools may often convey inadequate or misleading notions about the nature of science and the thought processes needed for it.

Fostering awareness of similarities and differences. A prime prerequisite for instructional improvements is to foster among teachers, textbook authors, and students a more explicit awareness of the similarities and differences between the domains of science and everyday life.

There are certainly appreciable similarities, because it is ultimately true that "science is nothing more than a refinement of everyday thinking." For example, as discussed in the preceding pages, both in everyday life and in science people try to explain and predict observable phenomena. Furthermore, in both domains these goals are pursued by exploiting knowledge consisting of various special concepts, by using suitable methods to solve diverse problems, and by trying to ensure adequate quality and efficiency of task performance.

But there are also substantial differences because several centuries of scientific development have resulted in major refinements beyond the level of everyday life. Indeed, an awareness of these differences is highly important to make appropriate discriminations and to avoid simplistic transfers of ways of thinking from everyday life into science, or vice versa.

Examples of such differences, apparent from our previous discussion, include the following: (a) Scientific goals, aiming to use minimal premises to achieve extensive predictions and explanations, are much more ambitious than the predictive and explanatory goals of everyday life. On the other hand, science does not directly deal with important human values relevant to the central everyday goal of leading a good life. (b) The scientific requirements of unambiguity, precision, consistency, and generality are much greater than those commonly needed in everyday life. Criteria of understanding and validity need thus correspondingly be more explicit. (c) Accordingly, the cognitive means needed in science are usually more deliberate, involving more explicitly defined concepts, more coherent knowledge structures, more highly formal and symbolic methods used in conjunction with nonformal methods, and more elaborate concerns with quality.

Teachers are often not sufficiently cognizant of these similarities and differences, and of the student learning difficulties resulting from them. Their central concern with teaching specific scientific knowledge often leaves little time for reflection about general issues, such as the distinctive characteristics of science and of everyday life. Furthermore, scientists immersed in research are often only tacitly aware of these issues and are usually not inclined to (nor even capable of) articulating them explicitly.

A more explicit awareness of these issues might at least help to reduce some of the inadvertently undesirable aspects of prevailing instructional methods, e.g., an excessive emphasis on factual knowledge or formal manipulations.

Instructional suggestions. An appreciation of the similarities and differences between the domains of science and everyday life suggests an instructional approach to reduce students' learning difficulties. Such an approach would specifically identify aspects of everyday life that are similar to those in science, and would aim to refine these systematically (with careful discriminations to avoid confusions or reversions to more primitive everyday knowledge). On the other hand, such an approach would also need to recognize other aspects of daily life that cannot be readily refined, to point out why they are deficient or inadequate in science, and to transcend them with more useful scientific conceptions.

The following are examples of similarities which can be exploited as bases of refinement. (a) Some kinds of explanations and methods used in daily life are sufficiently similar to those in science that they can be elaborated to be more scientifically satisfactory. (For instance, strategic and abstract planning is necessary for many games, including football and chess.) (b) Precision and rule-based behavior are not completely foreign to daily life. (For instance, precision is essential in dialing telephone numbers or balancing checkbooks, and rule-based behavior is common in chess or other games.) They can provide starting points for the more pervasive precision and rule-based thinking prevalent in science. (c) As already pointed out, nonformal methods are important in science as well as in everyday life. Thus they can be appropriately refined to ensure their consistency with more formal scientific knowledge and their complementary use with formal methods.

Explicit teaching of scientific metaknowledge. Finally, it would be desirable to teach students more explicitly about the goals of science and the kinds of thought processes useful in this domain. Such teaching could best be done in the context of actual science courses, because it would then lead to mutual benefits. (a) It would facilitate the learning of specific scientific principles and methods, because scientific arguments and ways of thinking seem often unmotivated and meaningless to students without an adequate appreciation of scientific goals. (b) Conversely, a discussion of scientific goals and thought processes would only be meaningful to students if repeatedly illustrated in the context of specific scientific problems and subject matter.

Teaching aimed at making students more explicitly aware of scientific goals and thought processes would clearly be a major challenge. It would require a long-term effort (probably extending over several science courses) where the teaching of specific scientific knowledge is embedded in a broader understanding of scientific goals and methods, and where daily work with scientific principles and problems constantly helps to illustrate scientific goals and ways of thinking. Such a teaching effort would be ambitious and difficult to implement. However, without some such efforts students are likely to acquire merely superficial scientific knowledge—without an adequate understanding of its purpose and without much ability to use it effectively.

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